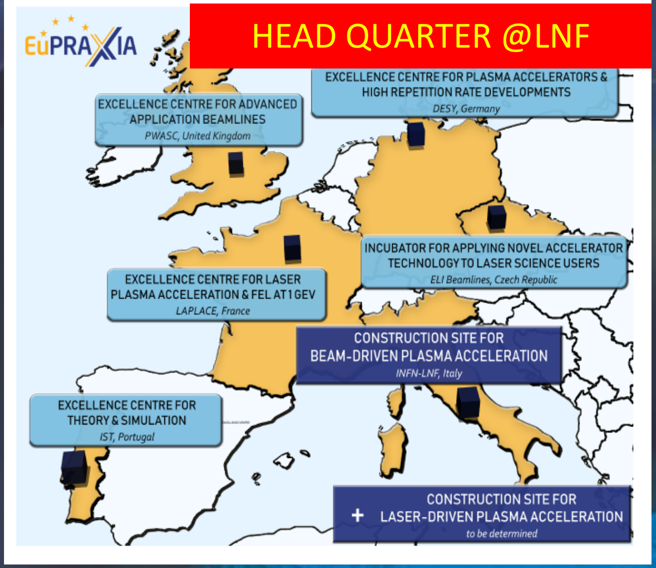
Status of the EuPRAXIA@SPARC_LAB Project:

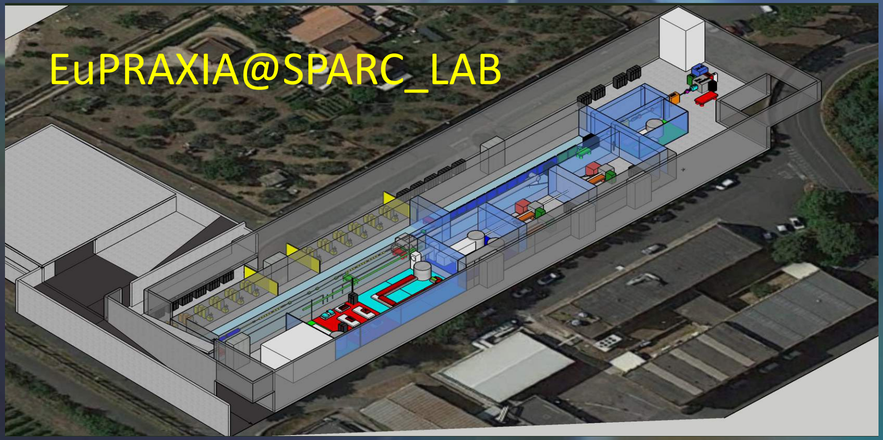
Massimo.Ferrario@LNF.INFN.IT

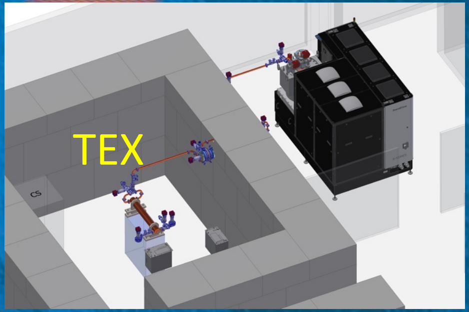
On behalf of the EuPRAXIA team

EuroNNAc Special topics Workshop, Elba, 21 September, 2022

HEAD QUARTER @LNF







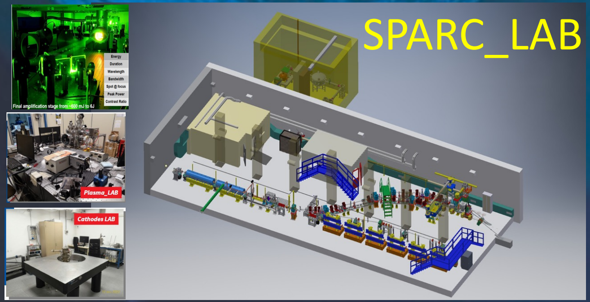

INFN
Istituto Nazionale di Fisica Nucleare

LNF–18/03
May 7, 2018

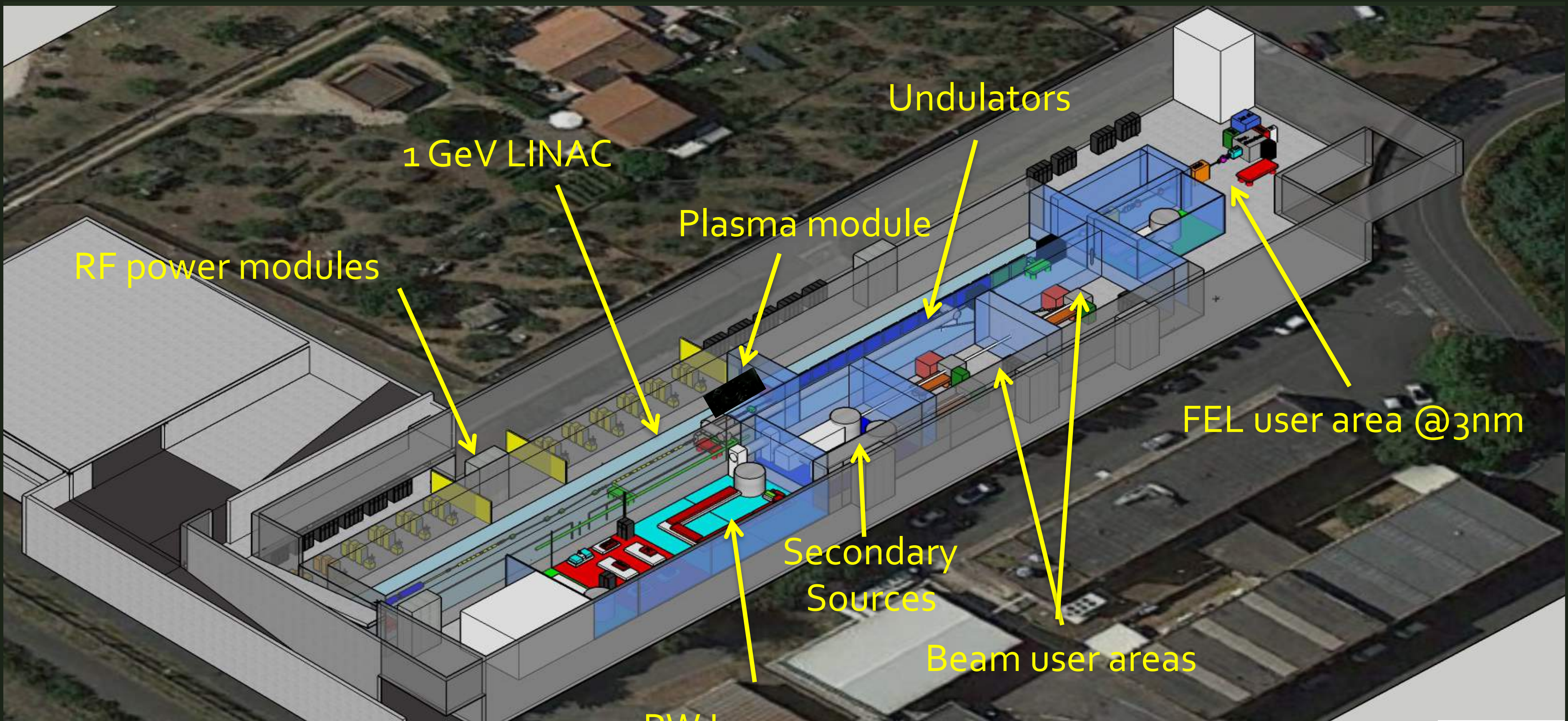
Technical Design Report

Finanziato dall'Unione europea
NextGenerationEU

REGIONE LAZIO



EuPRAXIA@SPARC_LAB



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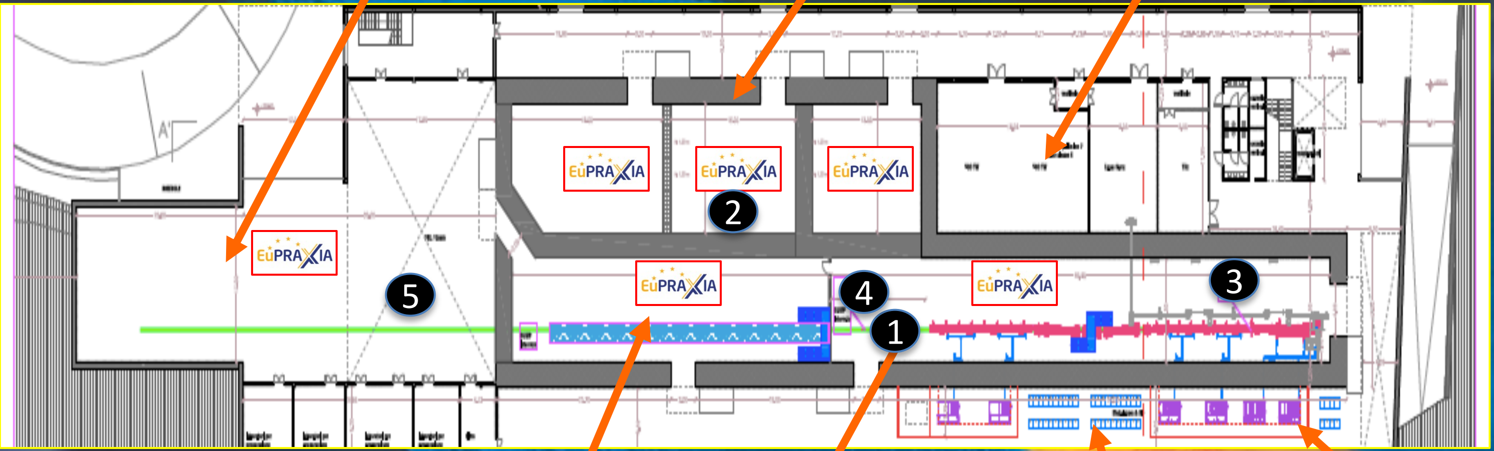
EuPRAXIA@SPARC_LAB

Conceptual Design Report

Opportunities for Collaborations at EuPRAXIA@SPARC_LAB



Laser & THz clean rooms

experimental halls

Photon user experimental hall

Undulators tunnel

Plant gallery

Accelerator tunnel

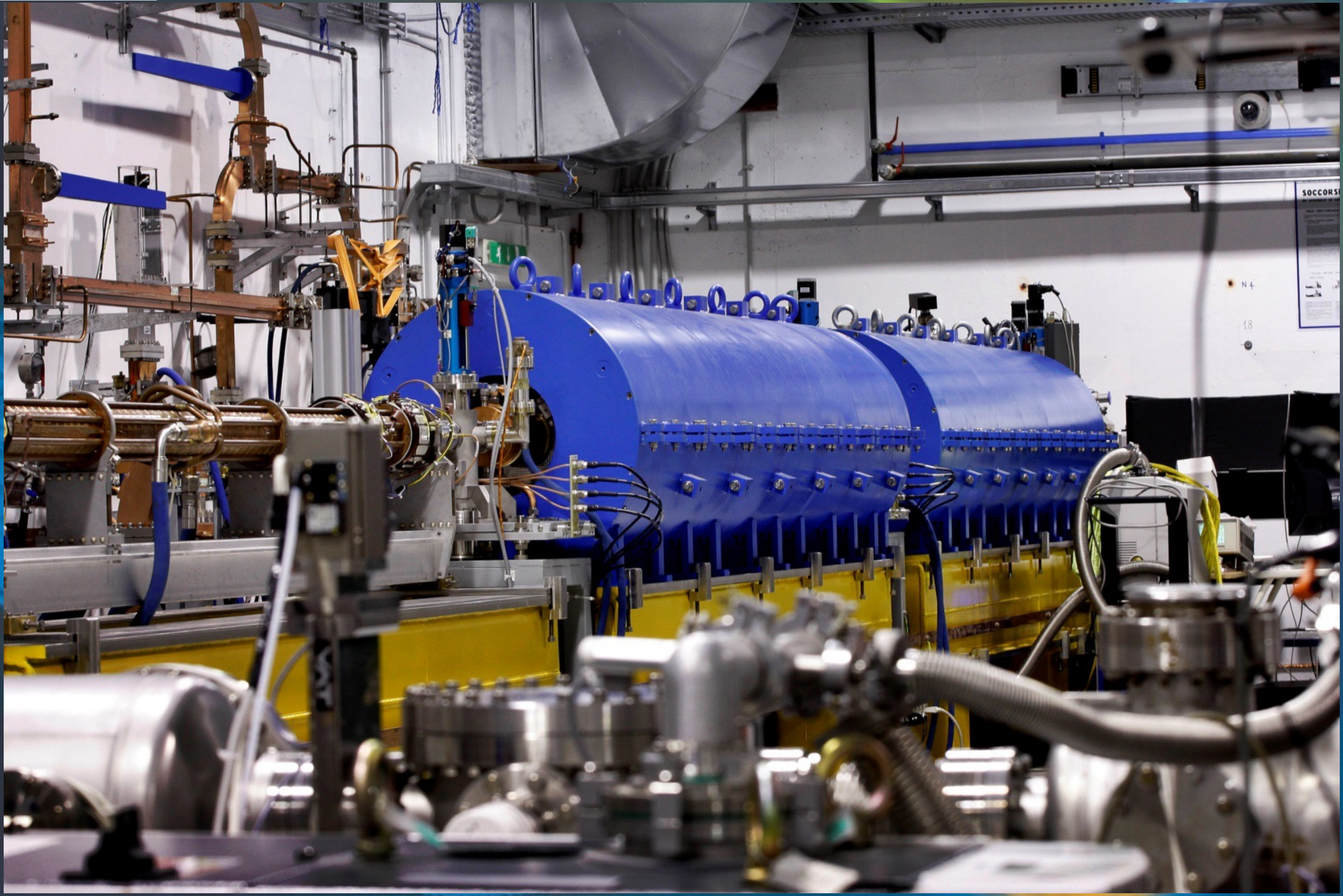
Klystron&modulators
Power supplies gallery

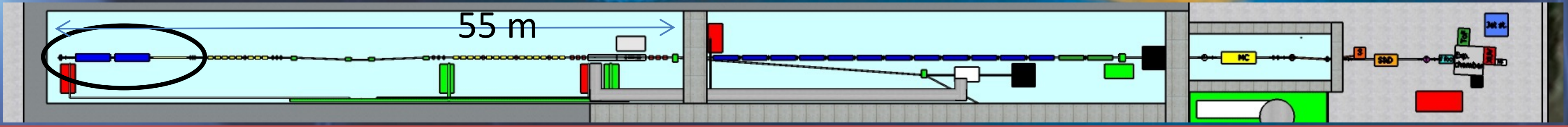
European interests & possible contributions to Frascati site:

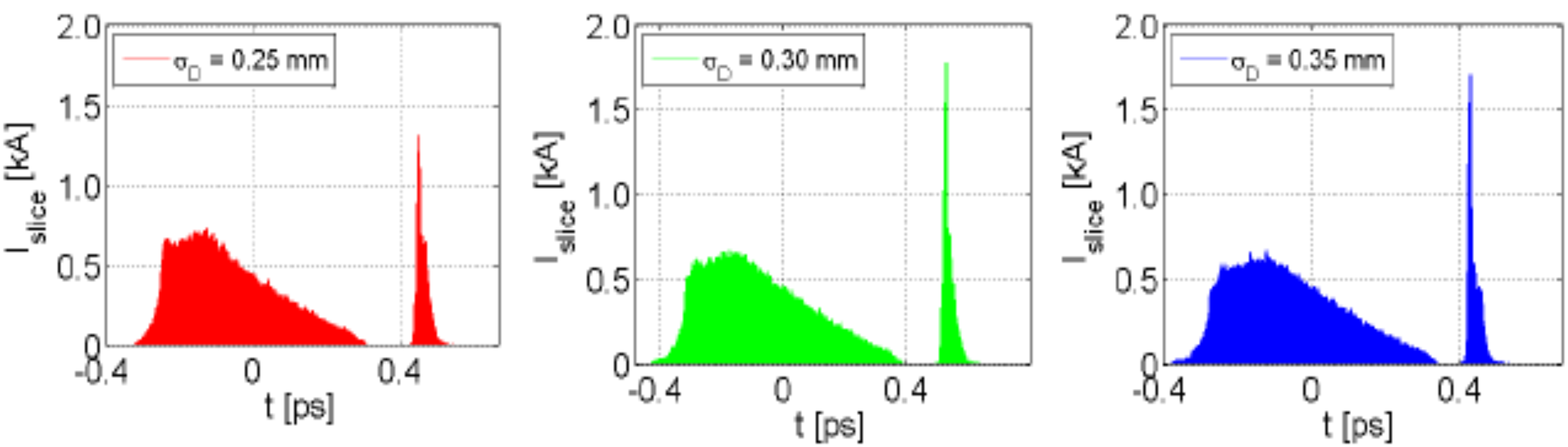
① Plasma structure designs, devices
② Compact positron source
③ HQ 150 MeV laser plasma injector
④ HQ laser driver
  - Hybrid concepts
  - Simulations
⑤ User experiments and lines

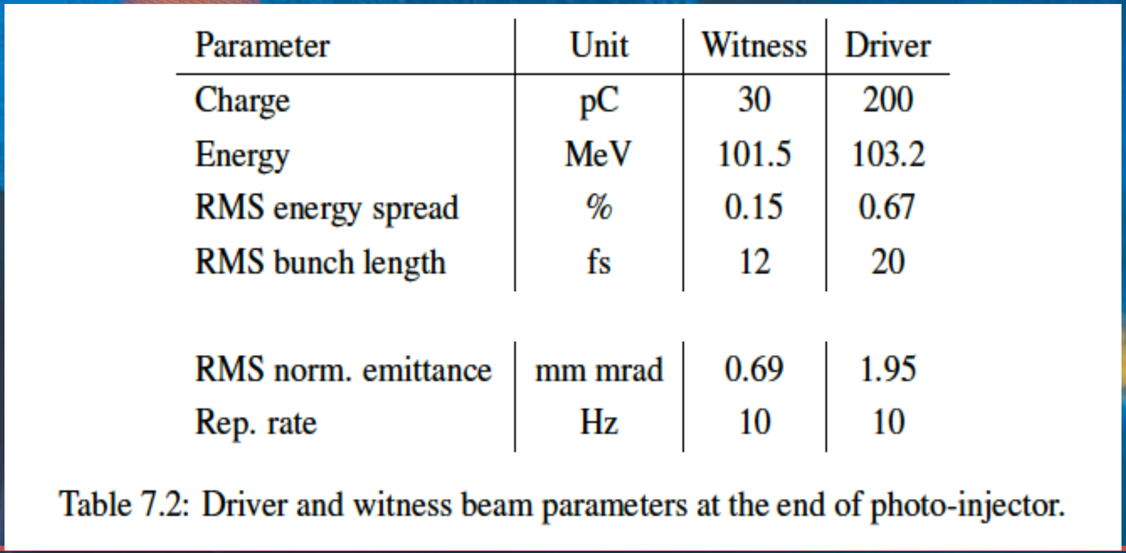
To be detailed in TDR phase.

SPARC_LAB HB photo- injector





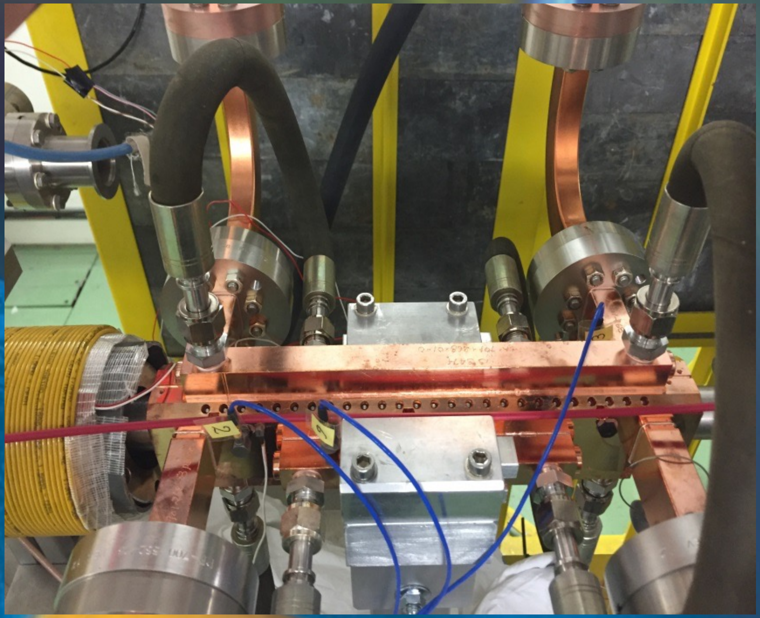


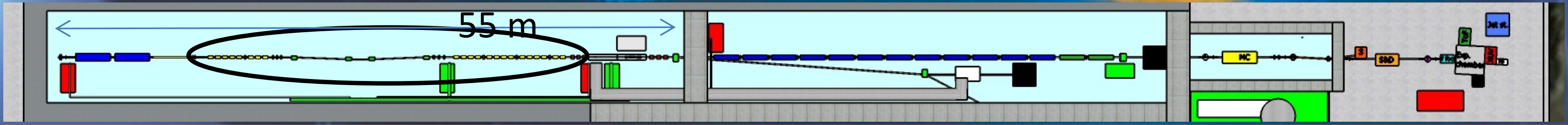


Parameter	Unit	Witness	Driver
Charge	pC	30	200
Energy	MeV	101.5	103.2
RMS energy spread	%	0.15	0.67
RMS bunch length	fs	12	20
RMS norm. emittance	mm mrad	0.69	1.95
Rep. rate	Hz	10	10

Table 7.2: Driver and witness beam parameters at the end of photo-injector.

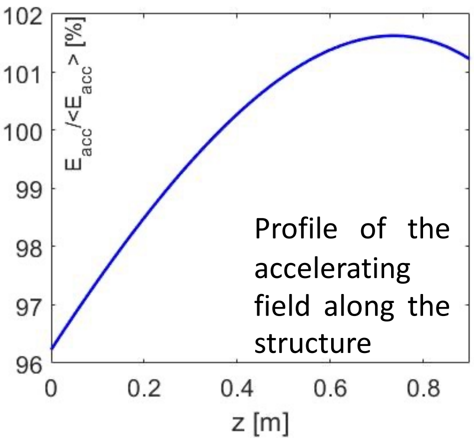
X-band Linac



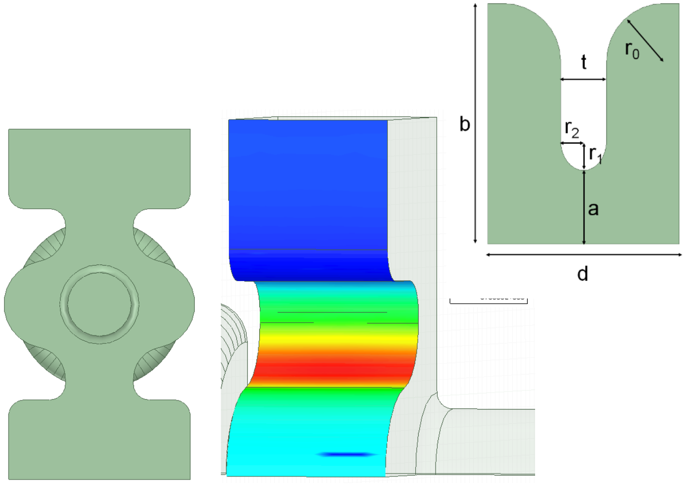


X BAND STRUCTURES: PARAMETERS

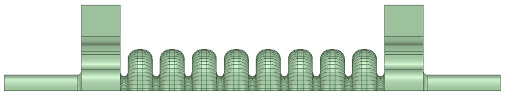
1. **e.m. design**: **linear tapering of the irises**, race track coupler to cancel the quadrupole field components (*PhD M. Diomede*);
2. **0.9 m long** structures with 3.5 mm average iris radius
3. **60 MV/m** average accelerating field

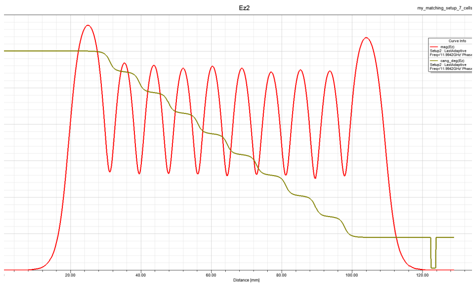


Profile of the accelerating field along the structure



Courtesy M. Diomede





Parameter	Value
Frequency [GHz]	11.9942
Average acc. gradient [MV/m]	**60**
Structures per module	4
Iris radius a (linear tapering) [mm] <a>=3.5	3.8-3.2
Tapering angle [deg]	0.04
Structure length L_s [m]	**0.9**
No. of cells	109
Shunt impedance R [MΩ/m]	94-107
Peak input power per structure [MW]	65
Input power averaged over the pulse [MW]	45
Average dissipated power [kW]	1
Filling time [ns]	126
Effective shunt Imp. R_s [MΩ/m]	350
Peak Modified Poynting Vector [W/μm²]	3.5
Unloaded SLED/BOC Q-factor Q_0	150000
External SLED/BOC Q-factor Q_E	21000
Required Kly power per module [MW]	**37/19**
RF pulse [μs]	**1.5**
Klystron power (available) [MW]	**50/25**
Rep. Rate [Hz]	**100**

$$R_s = \frac{G^2 L}{P_{kly}}$$

G=average accelerating gradient
L=structure length
P_{kly}=klystron power (pre-sled pulse)

RF Power Source

EuPRAXIA@SPARC_LAB has two main technological challenges:

- PLASMA Module
- X-Band RF Technology

TEX facility is currently working with a CPI Klystron on loan from CERN. An additional (at least) spare klystron is needed in order to guarantee continuity.

Opportunity to explore other solutions, better performances and possible upgrades in order to choose the baseline option.

TEX is also becoming a EOSC facility under FAIR principles (as requested by ESFRI for EuPRAXIA).

Collaboration with CNAF for data archiving

Development of a configuration tool (with LNL).

Cost & Performances comparison analysis

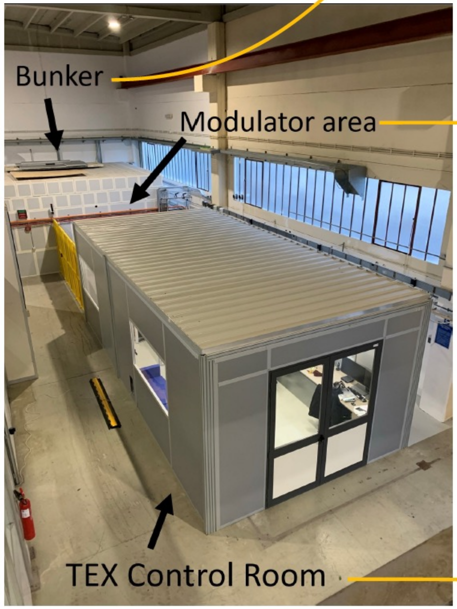
Parameter	Unit	Canon	CPI
Max Peak Power	MW	25	50
Max Repetition Rate	Hz	400	100
Number of station	#	20	10
Efficiency	%	40	60
Unit Cost *	k€	320	1085
RF Station Cost **	k€	975	1800
Cost / Peak power	k€/MW	39	35,6
Cost / Avg Power	k€/kW	65	237

* To be updated as the procurement process ends with the current price.

** For CANON case the number of total RF Stations is twice the CPI case.

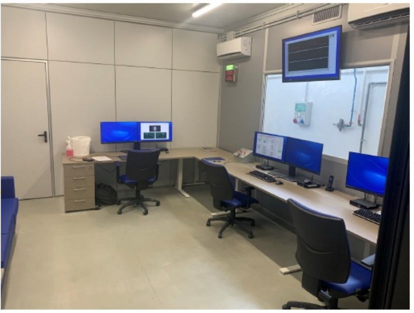
- CANON : 350k€ but additional K300 modulator + auxialiary utilities needed - tot. 1700k€
- CPI : 1250 k€. Can be marginally co-funded through CERN collaboration

TEX – TEst stand for X-Band



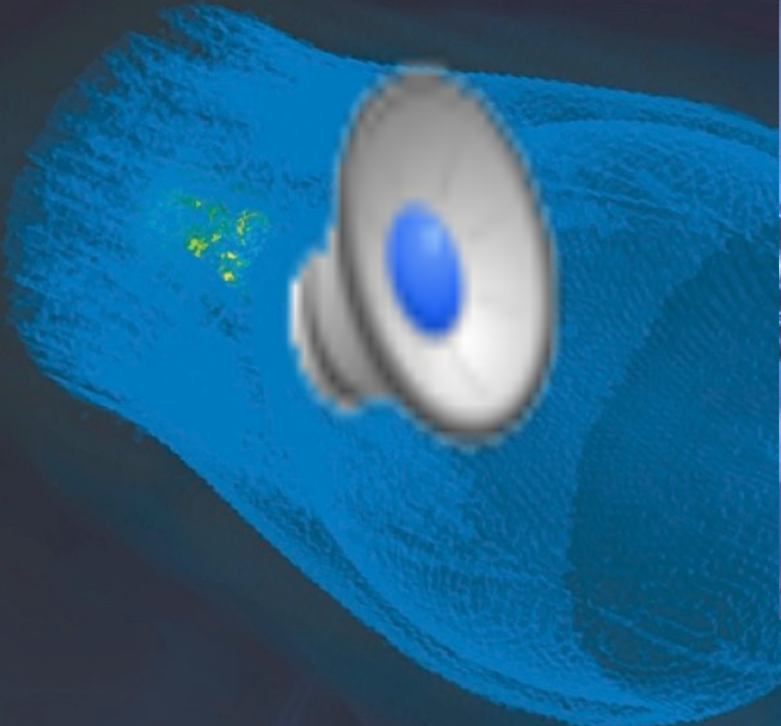
Courtesy F.Cardelli & S.Pioli

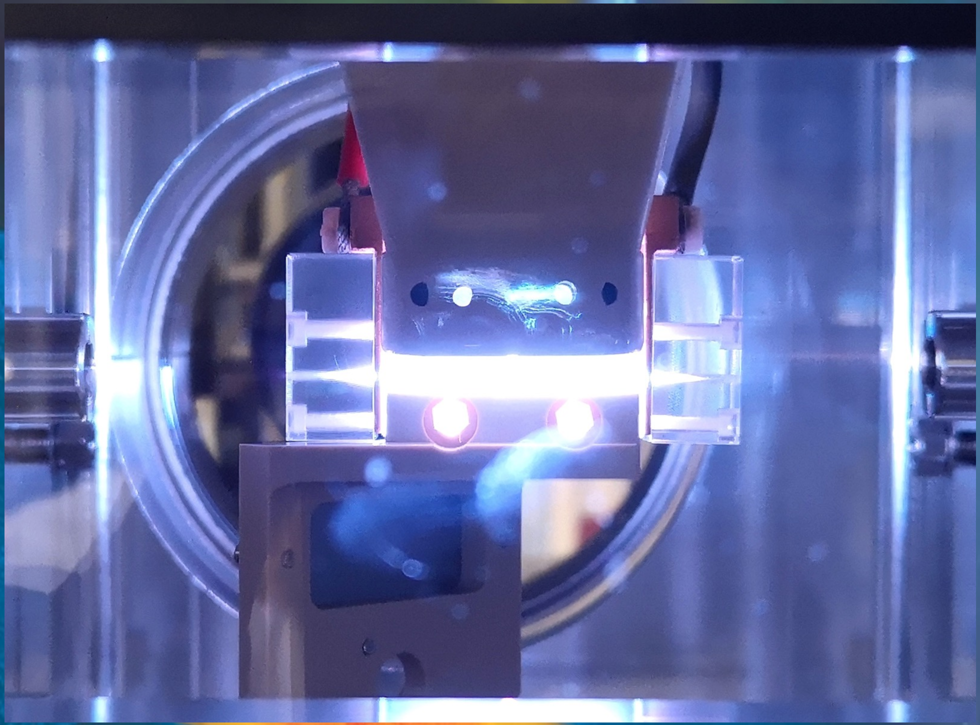
X-Band RF Source SAT
Successfully accomplished



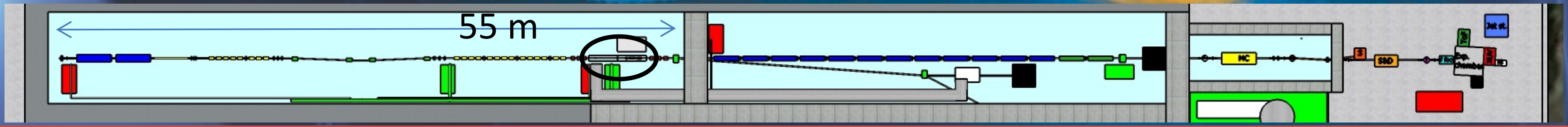
- The present TEX setup is based on:
  - K400 ScandiNova Modulator (HV pulses 430kV, 3.5us, 100Hz)
  - CPI VKX8311 Klystron (RF pulse 50MW, 1.5us, 50Hz)
  - Microwave Amplifier 1300 W solid state driver (SSD) amplifier
  - Commercial S-band LLRF system (ITech) adapted to work at 11.994 GHz with an Up/Down converter developed at LNF.

Plasma WakeField Acceleration





Capillary discharge at SPARC_LAB



March 2022 - First discharge in EuPRAXIA @ SPARC_LAB plasma acceleration module turned on

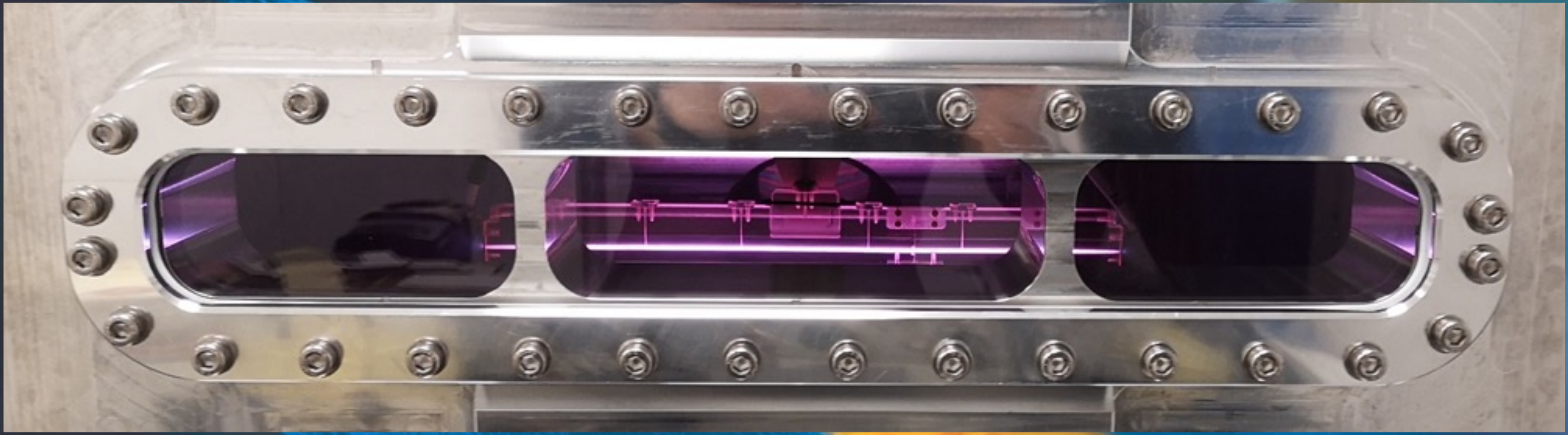
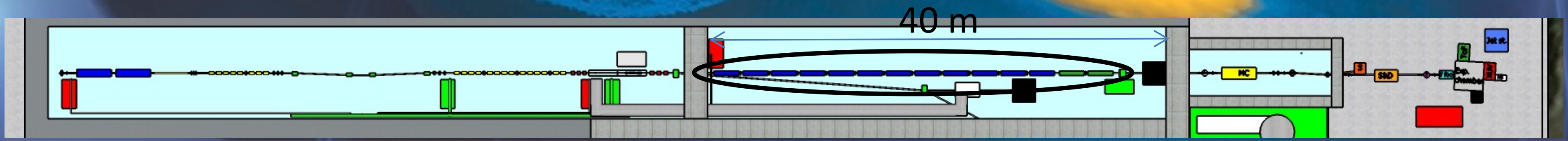


Image captured during the formation of plasma in the capillary 40 cm long and 2 mm in diameter, installed inside a vacuum chamber specially created to accommodate large plasma sources. The applied voltage pulse is 9 kV and the peak current reaches about 500 A.

Courtesy Angelo Biagioni

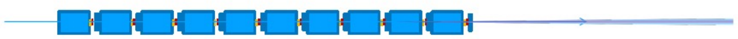
Undulators

KYMA Δ udulator at SPARC_LAB: λ=1.4 cm, K=1

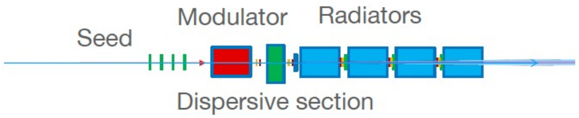


FEL | Ondulators

AQUA: **Soft-X ray SASE FEL – Water window 4 nm**

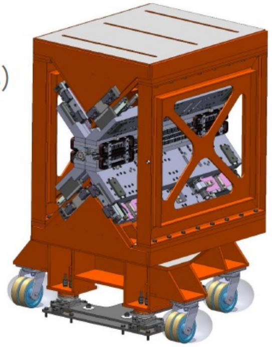


ARIA: **VUV seeded HGHG FEL beamline for gas phase** (not in the baseline)



Phase 1 – Apple X undulator for AQUA

- Baseline solution is an APPLE X Undulator / Period 18mm / 10 modules / 2m each
- Magnetic design studying:
  - Increasing #magnet per period 4 →6/8
  - Effect of mechanical deformation
  - Set-up appropriate magnetic measurement system.
- Prototyping (from Sabina undulators – KYMA design)
  - Define upper limits for acceptable deformation
  - Mitigate mechanical deformations associated to stresses
- Simulations
- Definition of intraundulators sections (e.g. diagnostics)

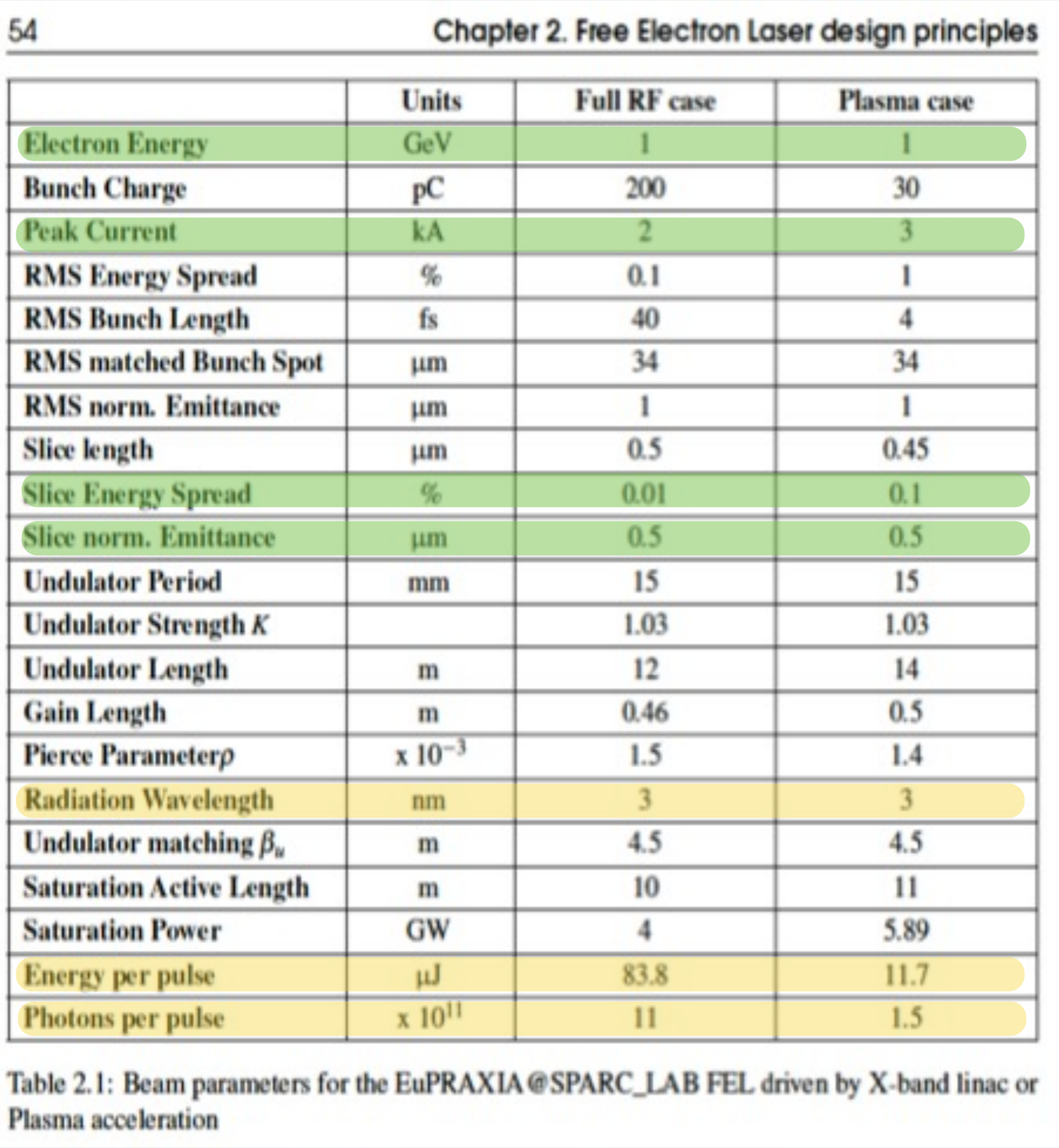


Prototype – Sabina ondulator (Kyma)

FEL Line	Configuration
AQUA	FEL Amplifier APPLE-X 18 mm period (+ SCU 1 module)
ARIA	HGHG FEL Modulator 3 m 10 cm period planar + 4 Apple 2 radiators, 6 cm period

Courtesy L.Giannessi

Expected SASE FEL performances

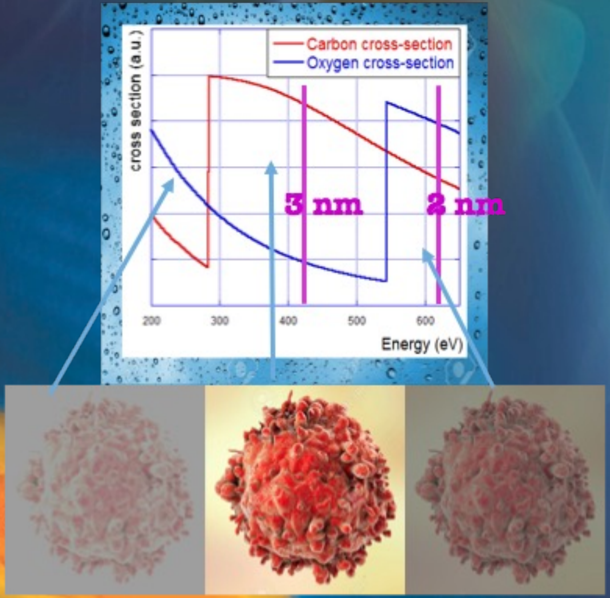


54 Chapter 2. Free Electron Laser design principles

	Units	Full RF case	Plasma case
Electron Energy	GeV	1	1
Bunch Charge	pC	200	30
Peak Current	kA	2	3
RMS Energy Spread	%	0.1	1
RMS Bunch Length	fs	40	4
RMS matched Bunch Spot	µm	34	34
RMS norm. Emittance	µm	1	1
Slice length	µm	0.5	0.45
Slice Energy Spread	%	0.01	0.1
Slice norm. Emittance	µm	0.5	0.5
Undulator Period	mm	15	15
Undulator Strength K		1.03	1.03
Undulator Length	m	12	14
Gain Length	m	0.46	0.5
Pierce Parameter ρ	x 10^{-3}	1.5	1.4
Radiation Wavelength	nm	3	3
Undulator matching β_u	m	4.5	4.5
Saturation Active Length	m	10	11
Saturation Power	GW	4	5.89
Energy per pulse	µJ	83.8	11.7
Photons per pulse	x 10^{11}	11	1.5

Table 2.1: Beam parameters for the EuPRAXIA@SPARC_LAB FEL driven by X-band linac or Plasma acceleration

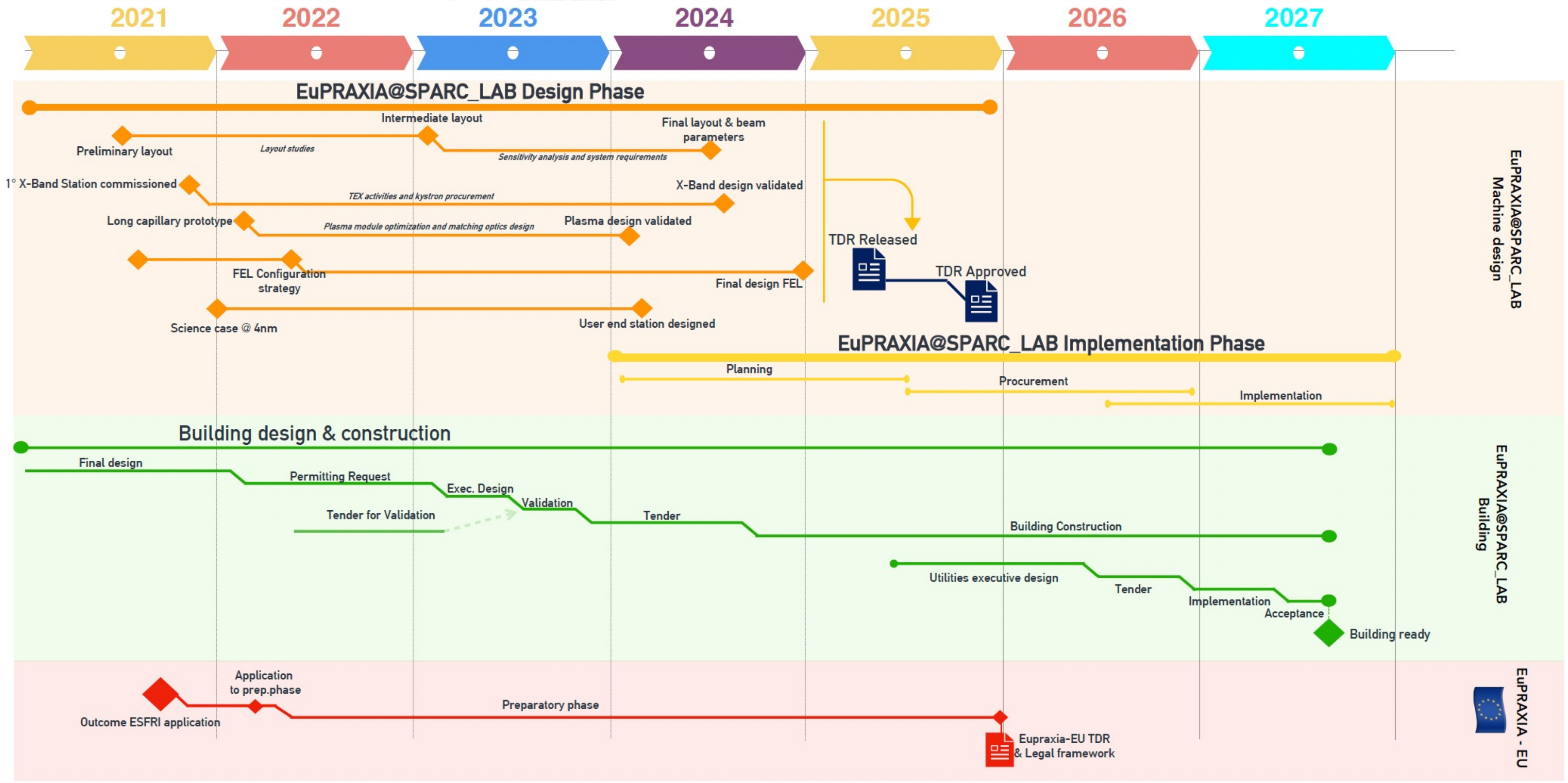
In the Energy region between Oxygen and Carbon K-edge 2.34 nm – 4.4 nm (530 eV -280 eV) water is almost transparent to radiation while nitrogen and carbon are absorbing (and scattering)



Coherent Imaging of biological samples protein clusters, VIRUSES and cells living in their native state
Possibility to study dynamics
~10^{11} photons/pulse needed

Courtesy F. Stellato, UniToV

Schedule update – critical milestones



2021
2022
2023
2024
2025
2026
2027

EuPRAXIA@SPARC_LAB Design Phase

Intermediate layout
Final layout & beam parameters
Preliminary layout
Layout studies
Sensitivity analysis and system requirements
1° X-Band Station commissioned
X-Band design validated
TEX activities and kystron procurement
Long capillary prototype
Plasma module optimization and matching optics design
Plasma design validated
TDR Released
FEL Configuration strategy
Final design FEL
TDR Approved
Science case @ 4nm
User end station designed

EuPRAXIA@SPARC_LAB Implementation Phase

Planning
Procurement
Implementation

EuPRAXIA@SPARC_LAB Machine design

Building design & construction

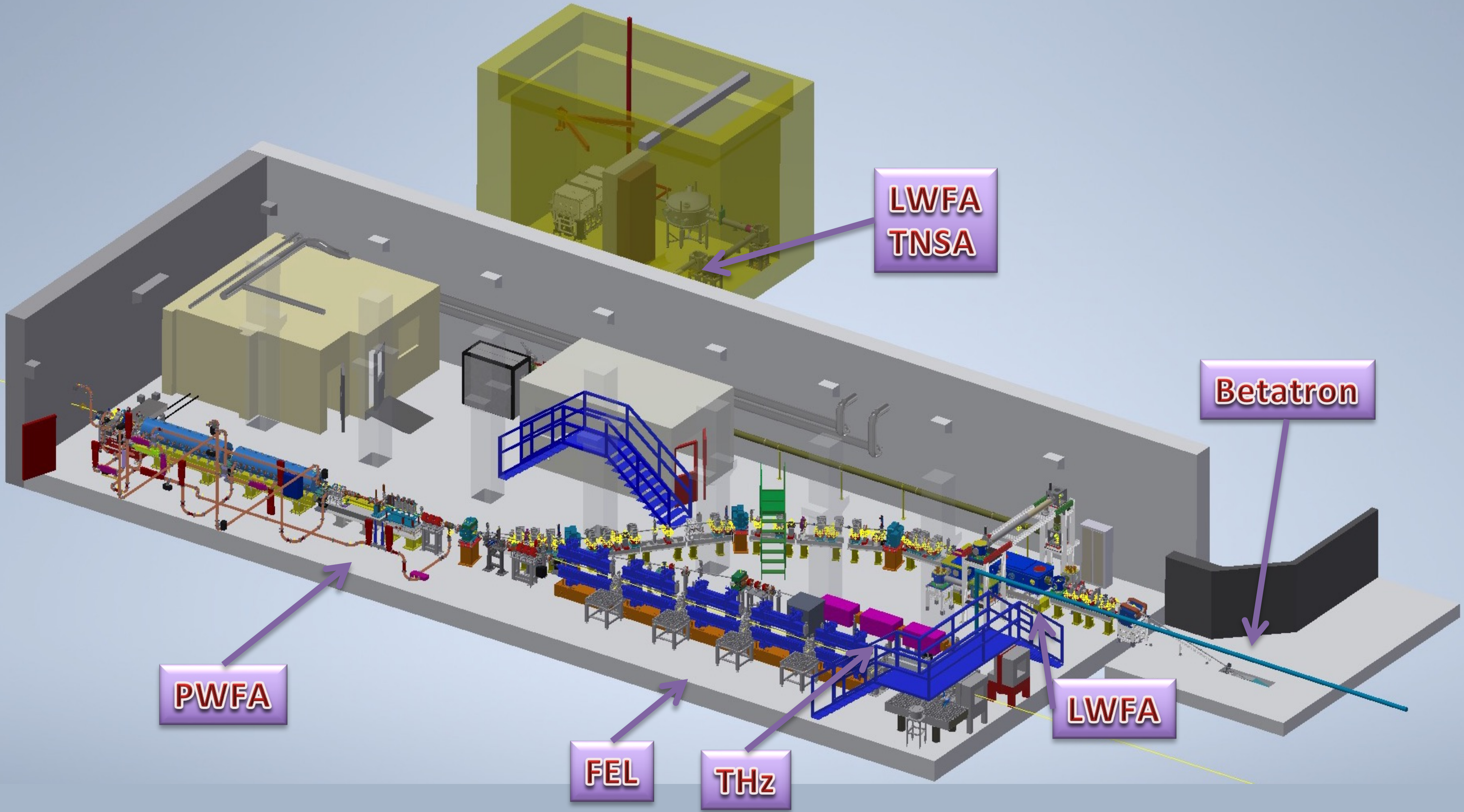
Final design
Permitting Request
Exec. Design
Validation
Tender for Validation
Tender
Building Construction
Utilities executive design
Tender
Implementation
Acceptance
Building ready

EuPRAXIA@SPARC_LAB Building

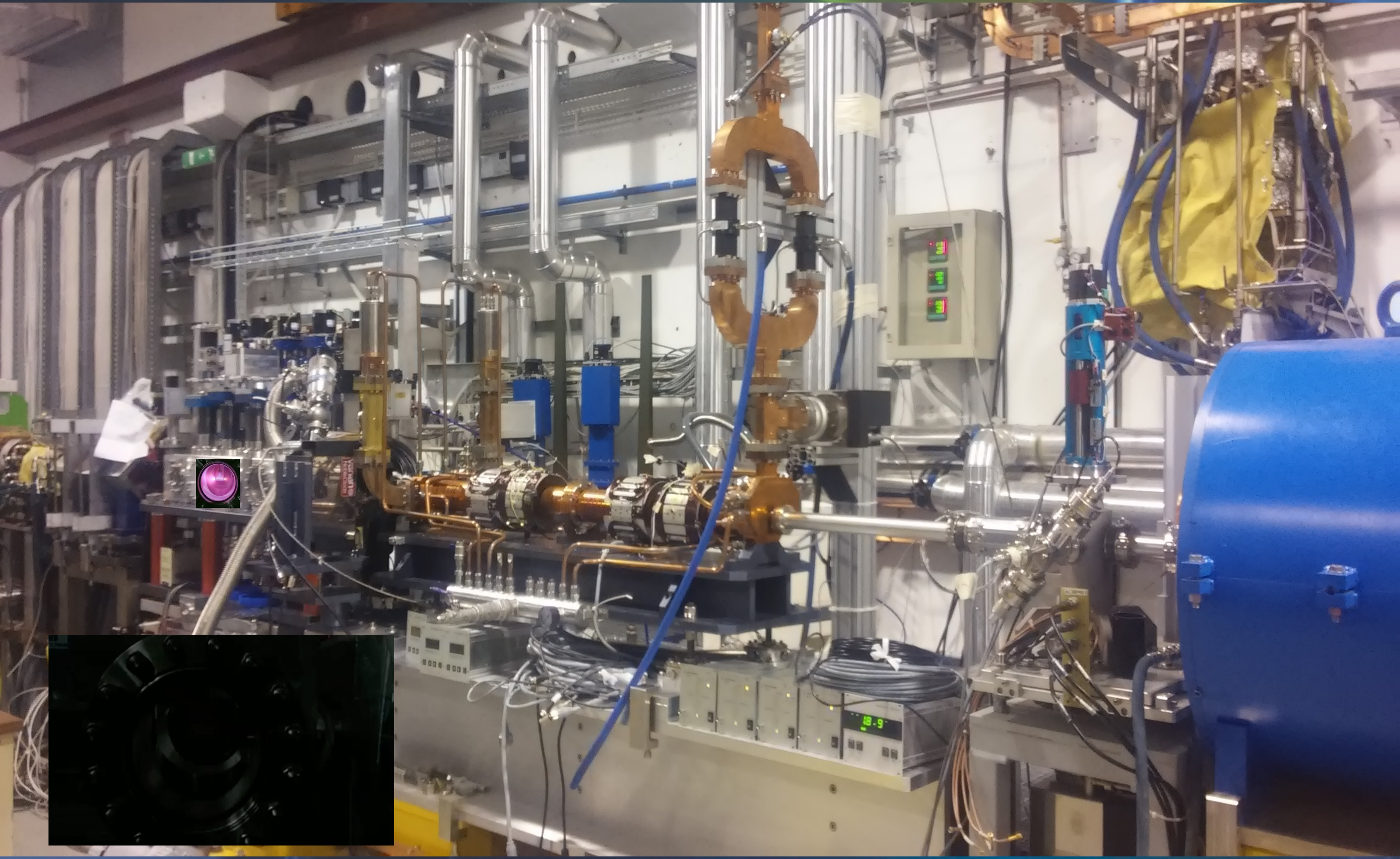
Application to prep.phase
Outcome ESFRI application
Preparatory phase
Eupraxia-EU TDR & Legal framework

EuPRAXIA - EU

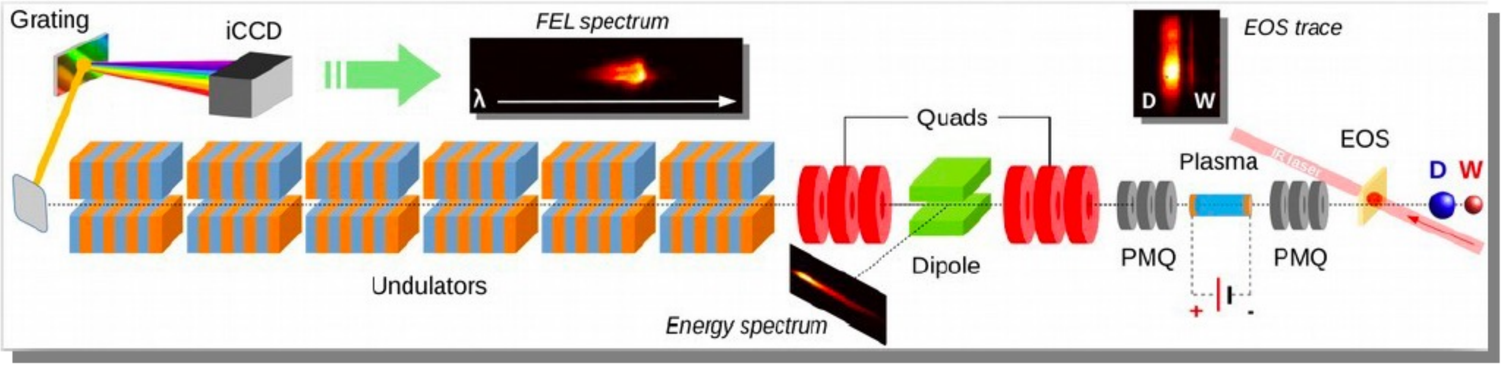
SPARC_LAB is the test and training facility at LNF for Advanced Accelerator Developments (since 2005)

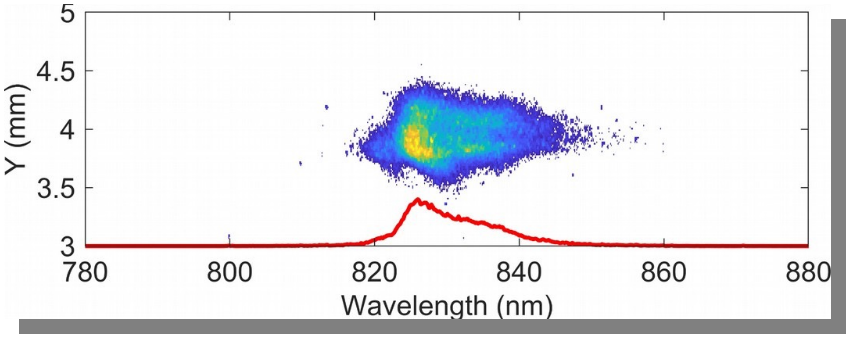


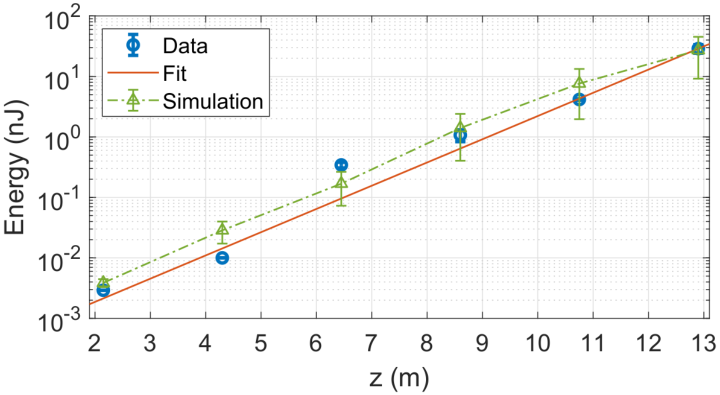
PWFA vacuum chamber at SPARC_LAB



First Beam Driven SASE-FEL Lasing at SPARC_LAB (May 2021)

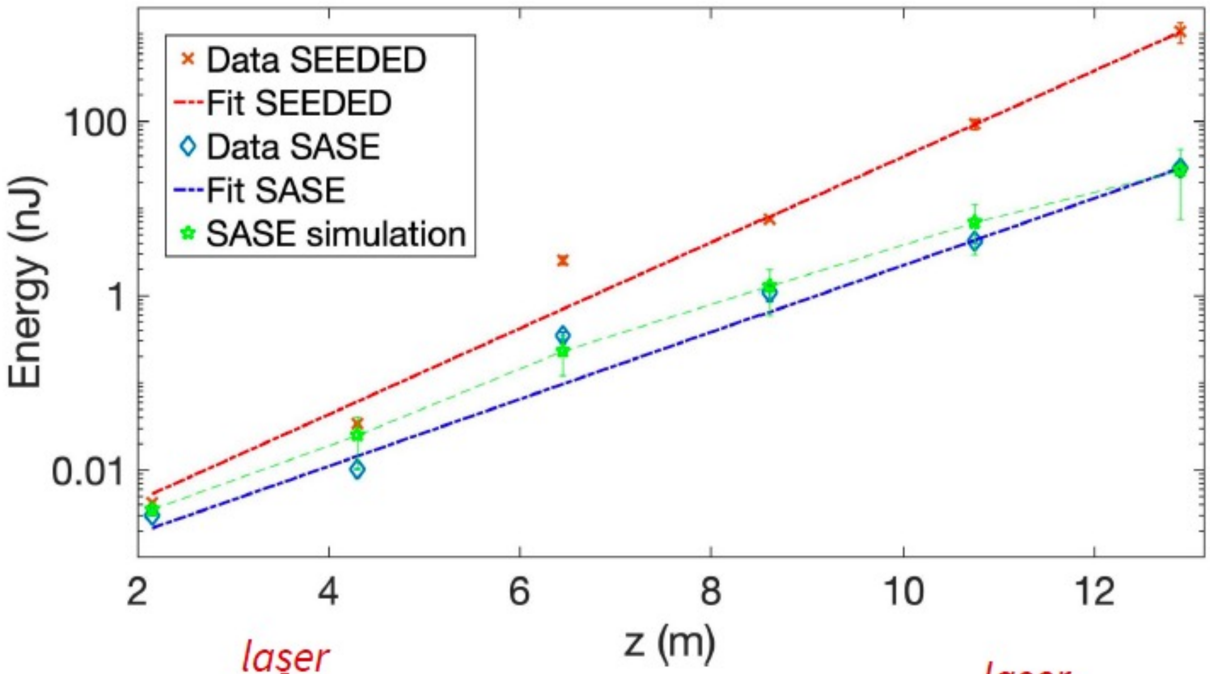






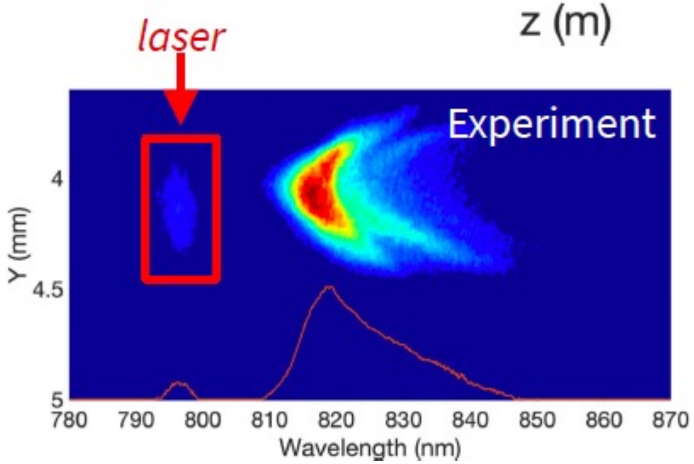
R. Pompili et al., Nature, May 26, 2022

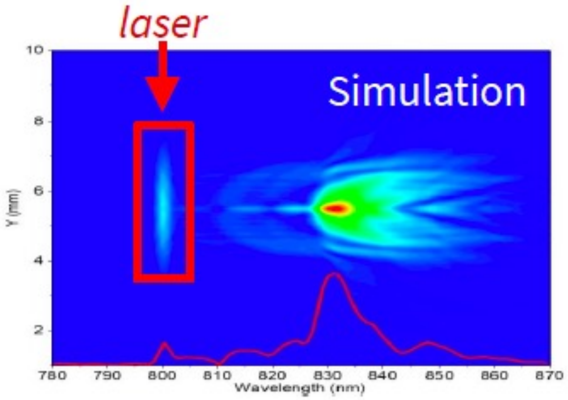
First Beam Driven SEEDED - FEL Lasing at SPARC_LAB (June 2021)



~1 uJ (SEEDED)

~30 nJ (SASE)





Betatron Radiation Source

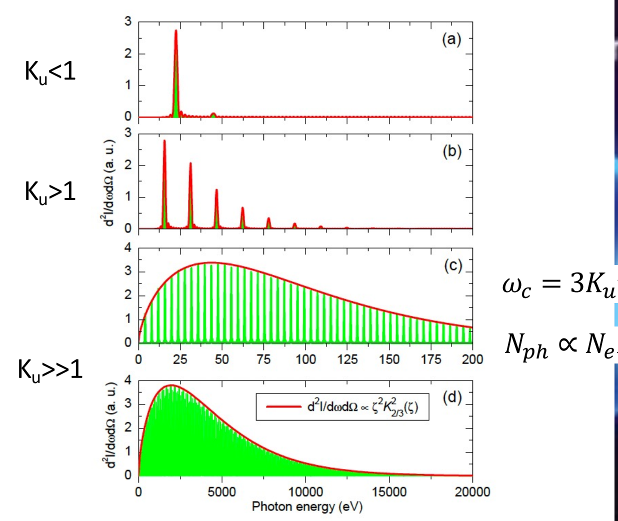
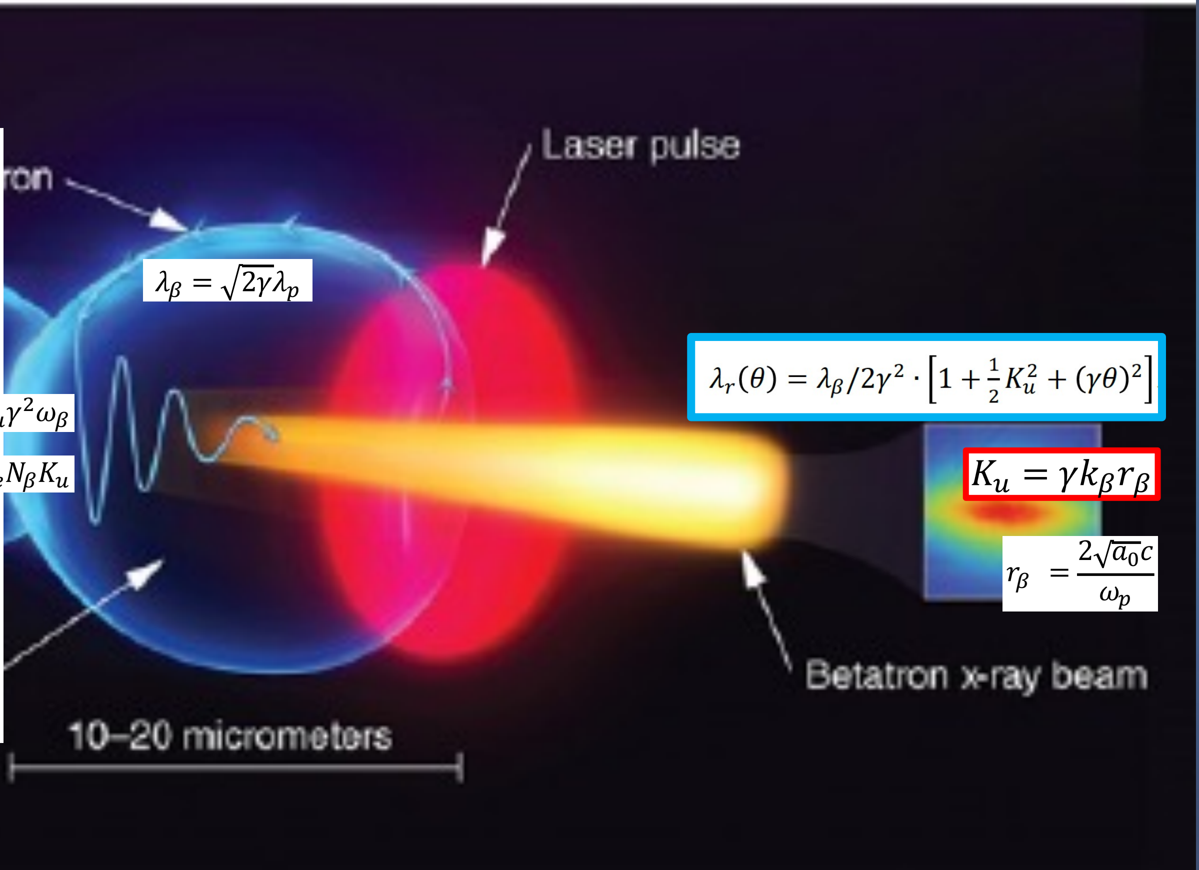


Figure 3.3: *Calculated betatron radiation spectra in a plasma column with density of 7×10^{18} cm^{-3}. The electron energy is 15 MeV, and oscillation amplitudes are (a) 0.1 µm, (b) 0.5 µm, and (c) 1.6 µm. (d) shows the case of a 100 MeV electron with an oscillation amplitude of 1.6 µm.*

$$\omega_c = 3K_u\gamma^2\omega_\beta$$

$$N_{ph} \propto N_e N_\beta K_u$$



$$\lambda_\beta = \sqrt{2\gamma}\lambda_p$$

$$\boxed{\lambda_r(\theta) = \lambda_\beta/2\gamma^2 \cdot \left[1+\tfrac{1}{2}K_u^2+(\gamma\theta)^2\right]}$$

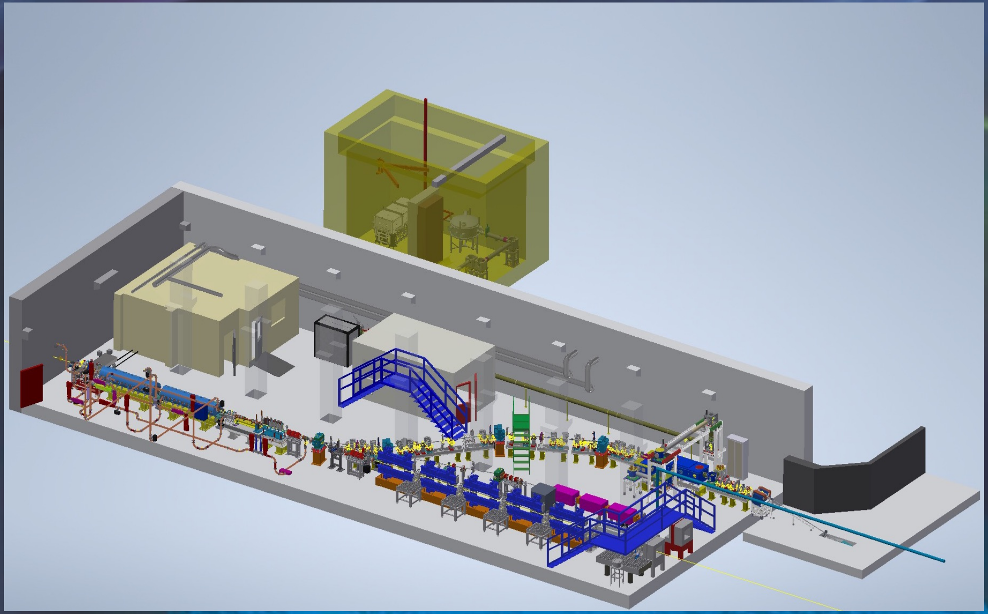
$$\boxed{K_u = \gamma k_\beta r_\beta}$$

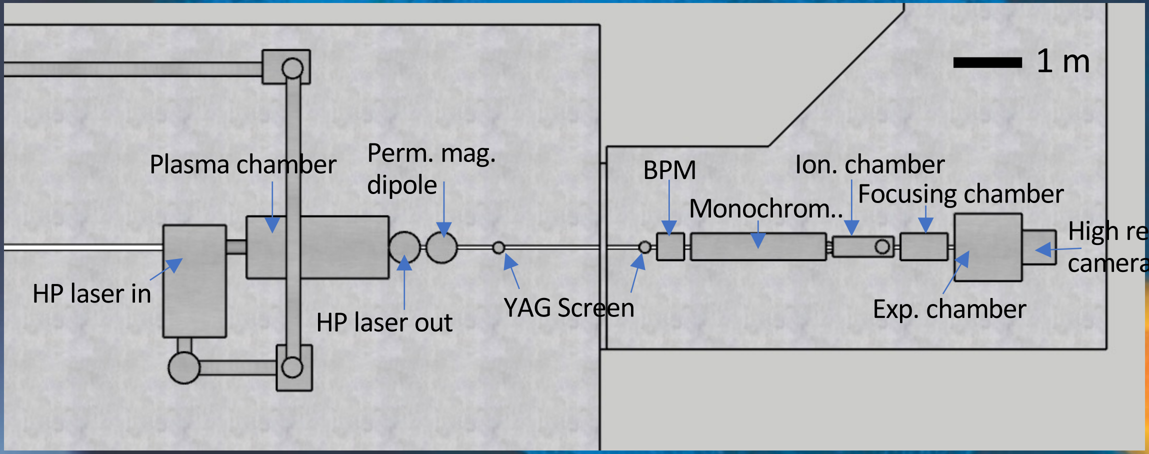
$$r_\beta = \frac{2\sqrt{a_0}c}{\omega_p}$$

LNF-LNS-MI

INO-ISM

Courtesy: Jinchuan Ju. Université Paris Sud - Paris XI, 2013

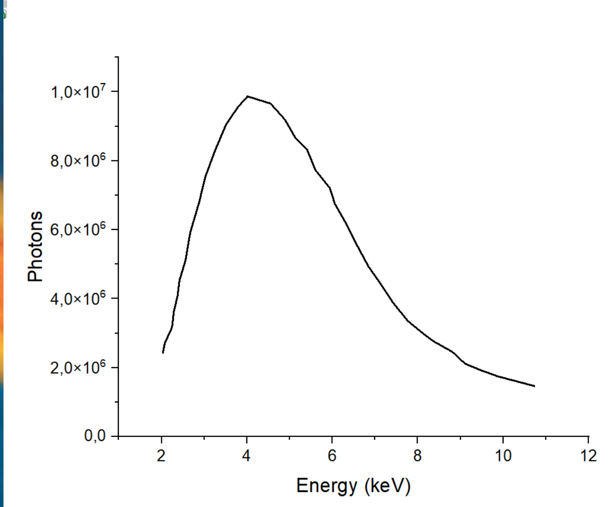




Electron beam Energy [MeV]	100-500
Plasma Density [cm^{-3}]	10^{17} - 10^{19}
Photon Critical Energy [keV]	1 - 10
Nuber of Photons/pulse	10^6 – 10^8

First measurements of betatron radiation at FLAME laser facility

A. Curcio [a,b,*], M. Anania [a], F. Bisesto [a,b], E. Chiadroni [a], A. Cianchi [a], M. Ferrario [a], F. Filippi [a,b], D. Giulietti [c], A. Marocchino [a], F. Mira [b], M. Petrarca [d], V. Shpakov [a], A. Zigler [a,e]



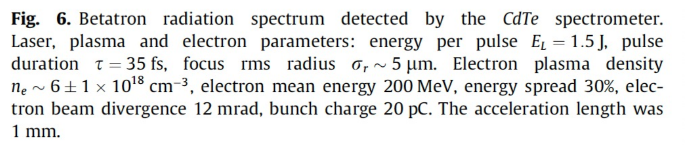
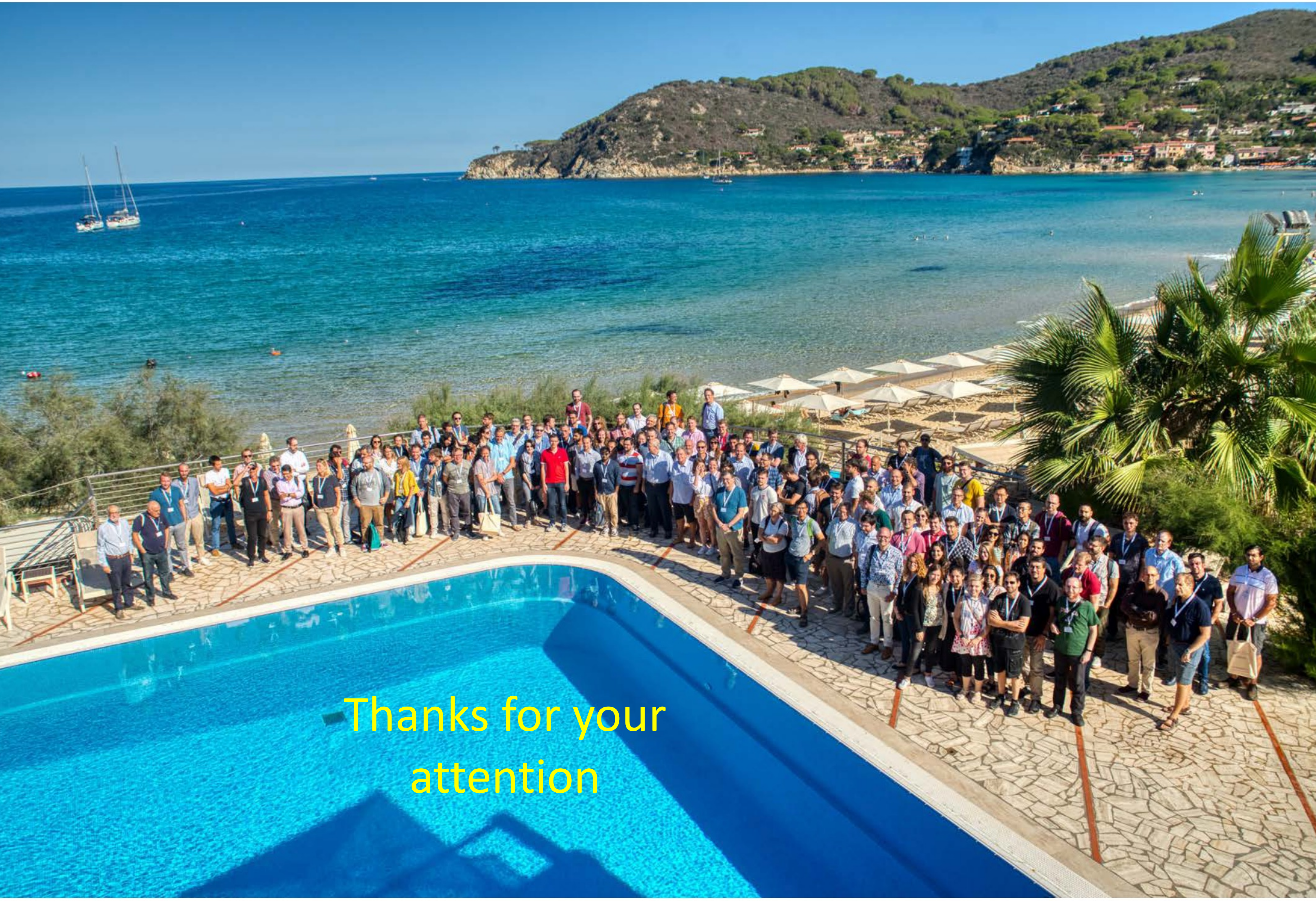


Fig. 6. Betatron radiation spectrum detected by the *CdTe* spectrometer. Laser, plasma and electron parameters: energy per pulse $E_L = 1.5$ J, pulse duration $\tau = 35$ fs, focus rms radius $\sigma_r \sim 5$ µm. Electron plasma density $n_e \sim 6 \pm 1 \times 10^{18}$ cm^{-3}, electron mean energy 200 MeV, energy spread 30%, electron beam divergence 12 mrad, bunch charge 20 pC. The acceleration length was 1 mm.

Conclusions

- A new era is just started at INFN-LNF with a strong focus on Advanced Radiation Sources development in the framework of EuPRAXIA.
- Consistent investement on R&D for Lasers, Plasma and High Gradient RF Structures has been already established.
- Stronger connection with the Universities et al. will be necessary to provide the required young scientists support for the next decade scientific challanges



Thanks for your attention